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# THERMAL REGIME AND CONVECTIVE MOTIONS IN THE LOWER LAYERS OF THE VENUSIAN ATMOSPHERE

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16. Abstract

The transfer of radiation in a flat layer of gas in the infrared where the surface spectral brightness of Venus is maximum and where the major $CO_2$ and $H_2O$ absorption bands exist, is analyzed in the assumption that the gas is transparent in the visible, far-ultraviolet and near-infrared bands of the solar spectrum and that the curvature of the surface layer of the atmosphere is negligible.

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# THERMAL REGIME AND CONVECTIVE MOTIONS IN THE LOWER LAYERS OF THE VENUSIAN ATMOSPHERE

V. S. Avduyevskiy, F. S. Zavelevich, M. Ya. Marov, A. I. Noykina, V. I. Polezhayev

Measurements of composition, temperature and pressure, conducted aboard /383* the Soviet unmanned space vehicle "Venera-4" [1, 2] make it possible to calculate the radiant heat fluxes in the atmosphere of Venus and to determine the possible zones of convective and radiant heat exchange. Assuming gas to be transparent in the visible, far ultraviolet and near infrared bands of the solar spectrum, and ignoring the curvature of the atmosphere in the surface layer, we will analyze the transfer of radiation in a flat layer of gas in the infrared ($4\ \mu \leq \lambda \leq 20\ \mu$), where the spectral brightness of the surface radiation of Venus for the measured temperatures is maximum, and where the major $CO_2$ and $H_2O$ absorption bands are found.

The absorption coefficients $\kappa$ for $CO_2$ and $H_2O$ were obtained on the basis of data [3-4]. The character of their change in the selected spectral interval is illustrated in Figure 1.

We will proceed from the equation of transfer of radiation, which in the stationary case for monochromatic radiation is of the form

$$\frac{dI_\nu}{ds} = \varkappa_\nu (I_{\nu_p} - I_\nu), \qquad (1)$$

where $I_\nu$ is the spectral intensity of radiation for ray S; $I_{\nu_p}$ is the Planck function.

This equation was solved numerically for selective radiation with space angle $\theta$ divided into six parts. The projection of spectral flux $q_\nu$ onto the normal to the surface of the planet is determined by solving the equation with upper and lower boundary conditions corresponding to the intensity of radiation in the orbit of Venus $I_{\nu_c}$ and at the surface $I_{\nu w}$, the blackness of which $\varepsilon =$ $= 0.9$:

$$q_\nu = 2\pi \int_0^\pi I_\nu \cos\theta \sin\theta \, d\theta, \qquad (2)$$

*Numbers in the margin indicate pagination in the foreign text.

and the total flux is determined by integrating the spectral fluxes in terms of frequency in the range of wave numbers from 500 to 2,500 $cm^{-1}$:

(3)

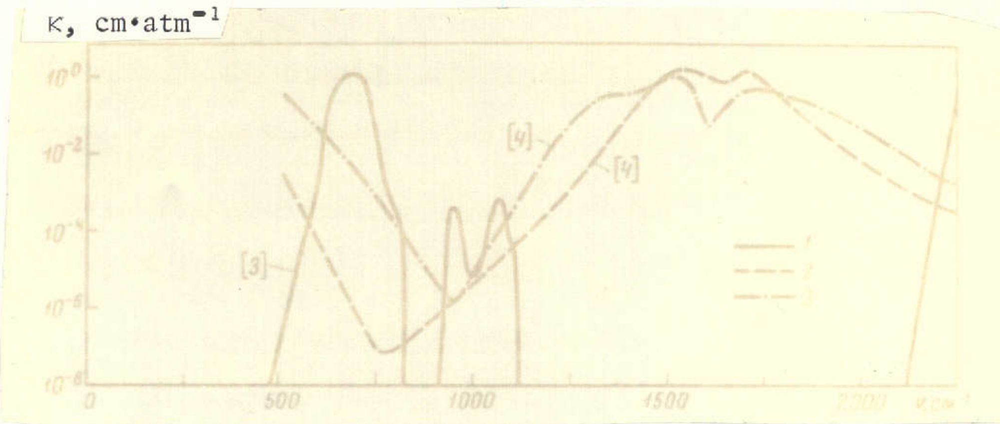


Figure 1. $CO_2$ and $H_2O$ Absorption Coefficients:
1, $CO_2$; 2, $H_2O$, T = 300°K; 3, $H_2O$, T = 600°K.

Presented in Figure 2 by way of example are the results of calculation of the distribution of $I_\nu$ for two models of the atmosphere, corresponding to surface temperature T = 535°K ($h_0$) and to the temperature extrapolated to 21 km below, T = 730°K for ($h_0$ - 21) km, and also at level $h_0$ + 20 km (T = 370°K) for these two cases.

The $CO_2$ bands occupy a small part of the examined range. Therefore, in the presence of just $CO_2$ the transfer of energy from the surface is great. The addition of 0.5% $H_2O$ leads to practically complete screening of radiation fluxes. We will see that because of the strong screening capacity of the atmosphere the radiant energy from the layers lying below the level $h_0$ contributes little to the flux passing through the upper layers.

This property of the atmosphere of Venus is demonstrated even more graphically in Figure 3, where the curves of distribution of radiation fluxes from the surface, calculated on the basis of the measured (a) and extrapolated (b) temperature for two water concentrations (0.1% and 0.5%), are presented. /385
Since radiation fluxes increase with altitude below the level of approximately

$h_0$ + 20 km, the condition of radiant equlibrium for stationary thermal regime q = const is not satisfied, and consequently it can be concluded that the thermal balance of the lower atmosphere of Venus cannot be attributed simply to radiant heat exchange.

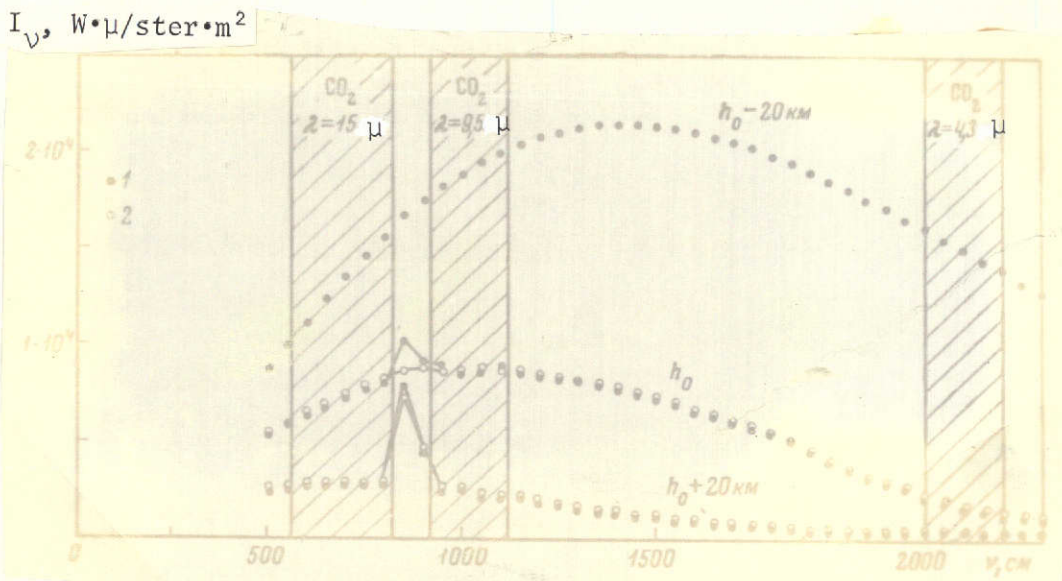


Figure 2. Intensity of Radiation in Atmospheric Gas at Various Altitudes: 1, T = 730°K; 2, T = 535°K.

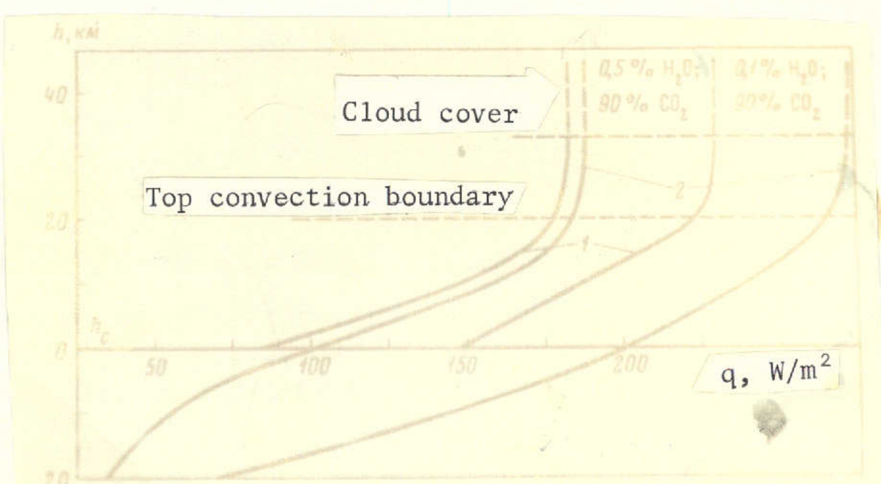


Figure 3. Radiation Fluxes Calculated for Measured (1) and Extrapolated (2) Temperature Distributions of Atmosphere by Altitude.

The strong dependence of radiation fluxes at the upper boundary of the atmosphere of the planet on the $H_2O$ concentration is clearly illustrated in Figure 4, where the albedo values A of Venus, corresponding to $q_{rad}$, determined from the thermal balance of a rotating planet, are presented. Unrealistic radiation fluxes are obtained for pure $CO_2$ ($q \simeq$ 4,450-7,000 $W/m^2$). The $H_2O$ concentration of 0.5% corresponds to A = 0.76-0.78, and for 0.1% $H_2O$ we have A = 0.64-0.7.

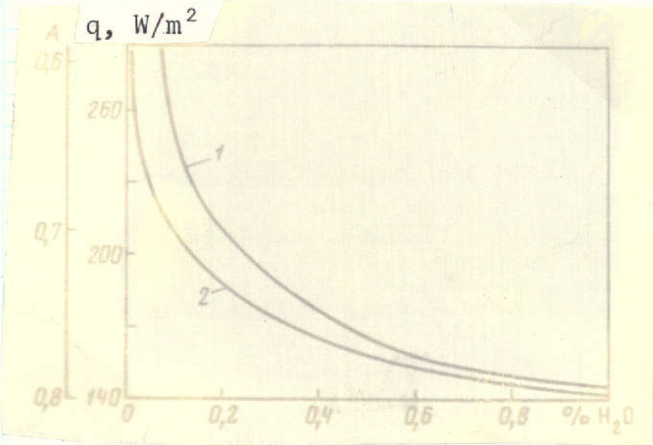


Figure 4. Effect of Water Concentration on Radiation Flux: 1, T = 730°K; 2, T = = 535°K.

The temperature profile in the atmosphere of Venus, which should correspond to the condition of purely radiant equilibrium, was calculated by the method of successive approximations on the basis of the relations written above and the equations of state and hydrostatics. The temperature profile, calculated by the stated method, is compared with the measured profile in Figure 5. As we see, the temperature of the gas at the surface increased to 580° and the average vertical temperature gradient increased correspondingly. Especially large values, much greater than the adiabatic gradient, are reached at the surface. Strong convective motions should be /386
generated in this region, since thermal equilibrium can be ensured only through additional heat transfer.

Let us examine a model of a convective cell with characteristic height and width dimensions L, approximately equal to the altitude of a homogeneous atmosphere. The side walls of the cell are heat-insulated, the temperature at the top boundary $T_1$ = const, heat flux $q_w$ is supplied from the bottom and the velocities on the boundaries of the cell are zero.

As the characteristic of the motive force of free convective motions in the gravity field of Venus we will use the ratio of the adiabatic and radiant temperature gradients:

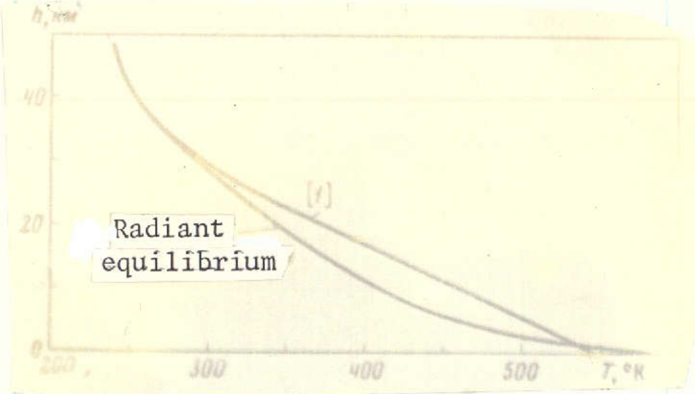


Figure 5. Temperature Profiles of Atmosphere Corresponding to Measured Values [1] and State of Radiant Equilibrium.

$$K = \frac{(\partial T/\partial y)_{ad}}{(\partial T/\partial y)_r}.$$

Then the dimensionless velocity of convective motions in the general case is a function of three determining similarity criteria: K, Grashof number $Gr_L$ and compressibility criterion $C_F$, and may be written in the form

$$\frac{V}{\sqrt{\gamma R T_1}} = \Phi(K, Gr_L, C_F).$$

The motion and transfer of heat by convection for the selected cell was calculated on the basis of the equations of momentum in projections onto the X and Y axes, equation of continuity and equation of energy with consideration of thermal conductivity, viscosity and compressibility of gas, together with the equation of state.

For $L \simeq H$ = 10-12 km we have $C_F \sim 1$ and $Gr \simeq 10^{21}$-$10^{22}$, so that the motion is *a fortiori* turbulent.

Since it is not possible at the present time to do calculations for the stated Gr numbers, the calculations were done for Gr numbers up to $10^6$ in the assumption that the dependence of V on K and $C_F$ remains qualitatively analogical. Stationary conditions were achieved as a result of establishment of the initial disturbances [5, 6].

The results of the calculations are presented in the following figures. /387

Figure 6 shows the boundary of convection in a convective cell for the ratio of the surface temperature and top boundary temperature of 1.5. Convective motions may occur only in the range of $Gr_L$ and $C_F$ numbers above curve 1. An example of the establishment of the convective profile in this model for K = 0.56 is illustrated in Figure 7. We see that in the nucleus of developed convective motion is established temperature gradient (3), close to adiabatic

(2), and near the boundaries the temperature gradient in the gas exceeds adiabatic and approaches initial radiant (1).

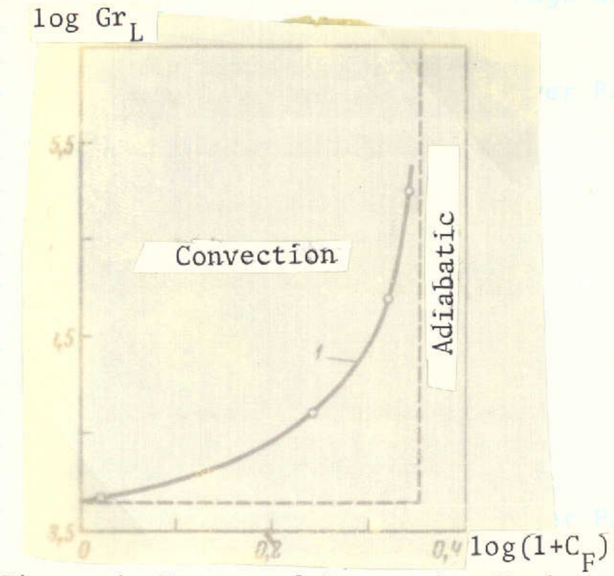


Figure 6. Ranges of Convective Motions in Compressible Gas (above curve 1).

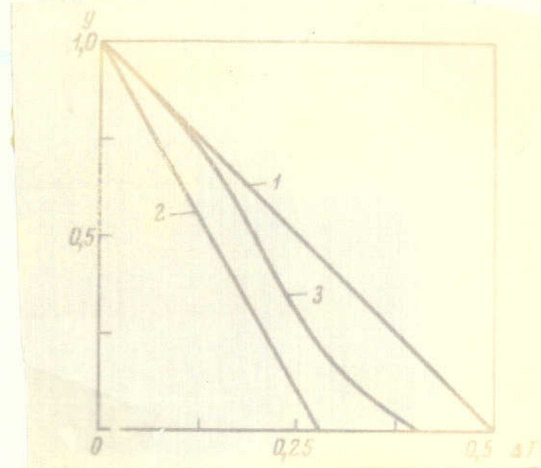


Figure 7. Temperature Profiles in Convective Cell under Various Conditions: 1, Initial radiant; 2, Adiabatic; 3, Convective.

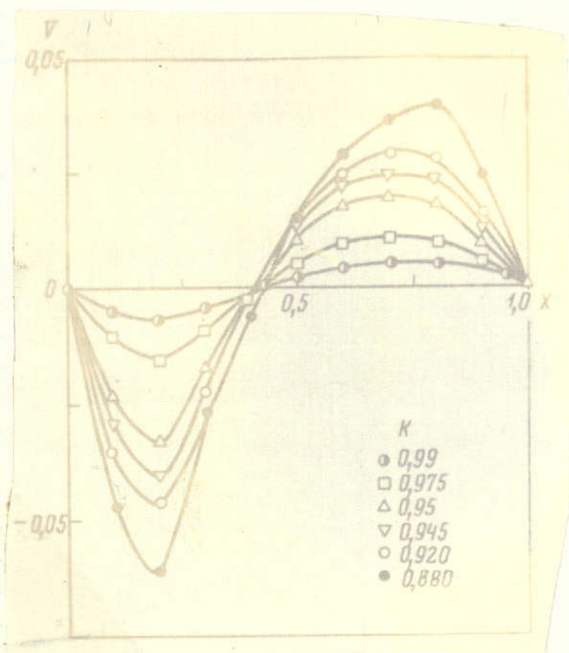


Figure 8. Change of Vertical Convection Velocity Profile as Function of Parameter K.

As K decreases the intensity of convective motions (for $C_F \sim 1$) increase considerably. This is illustrated in Figure 8, where the horizontal distribution of velocity V of vertical convection at altitude L/2 is shown, and in Figure 9, which shows the possible variations of the model structure of convective cells and the dependence of velocity $V_{max}$ on K for single-vortex and double-vortex motion. The latter is excited by symmetrical initial disturbances at high critical values of $Gr_L$ and $C_F$.

The curves in Figure 9 can be used for qualitative evaluation of the intensity of convection in the atmosphere of Venus. Obviously, considerable changes of velocity may correspond to small deviations from K = 1 (equilibrium state). For K = 0.99, for example, which corresponds to a deviation of 0.1 deg/km from the adiabatic gradient, the rate of convective motions is about 1.5 m/s.

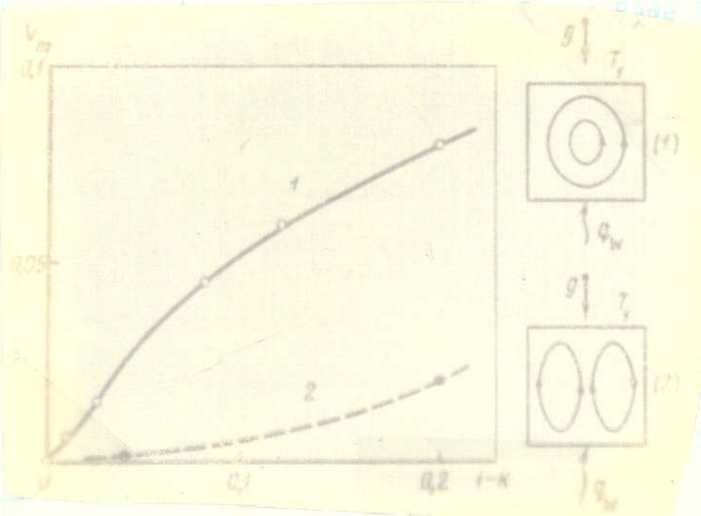

Figure 9. Maximum Amplitude of Vertical Convective Motions as Function of K: 1, Cell with one vortex; 2, Cell with two vortexes.

The possible change of the rate of convection with altitude, corresponding to the results of the calculations presented above, is illustrated in Figure 10. The distribution of parameter K was computed according to the local gradients of the temperature profile in radiant equilibrium (Figure 5) and adiabatic profile, calculated in [1]. The rate of convective motions is maximum at the surface, where K ≃ 0.3, and diminishes with altitude to zero near 8 km. The latter result apparently should be attributed to the calculation model that was used. Actually, the curves of the radiation flux distribution presented in Figure 3 show that equalization of the thermal profile must occur up to the altitude of ($h_0$ + + 20) km. This equalization may be related to the penetrating character of the convective motions and mutual influence of radiation and convection, just as much as it is to large real Grashof numbers. A more accurate solution of this problem with consideration of the above-stated factors is the purpose of our future studies. /388

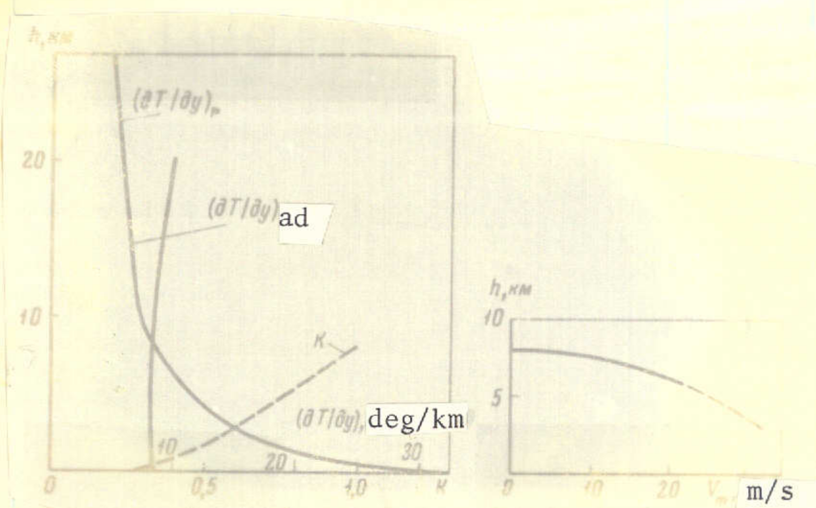


Figure 10. Change of Rate of Convective Motions as Function of Altitude.

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